

# **The Role of Proton Precipitation in Jovian Aurora: Theory and Observation**

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## **Abstract**

Goertz [1980] proposed that the Jovian auroral emissions observed by Voyager spacecraft could be explained by energetic protons precipitating into the upper atmosphere of Jupiter. Such precipitation of energetic protons results in Doppler-shifted Lyman alpha emission that can be quantitatively analyzed to determine the energy flux and energy distribution of the incoming particle beam. Modeling of the expected emission from a reasonably chosen Voyager energetic proton spectrum can be used in conjunction with International Ultraviolet Explorer (IUE) observations, which show a relative lack of red-shifted Lyman alpha emission, to set upper limits on the amount of proton precipitation taking place in the Jovian aurora. Such calculations indicate that less than 10% of the ultraviolet auroral emissions at Jupiter can be explained by proton precipitation.

## Introduction

The first theoretical estimate of the contribution of proton precipitation to Jupiter's aurora was offered by Heaps et al.[1975]. A further theoretical study based on in situ observations of the Voyager plasma and fields experiments suggested the presence of strong proton aurora on Jupiter's night side [Goertz, 1980]. However, since the time of Goertz's original Voyager-inspired analysis, additional evidence has been gathered for the contribution of heavy ion ( $S^{+q}$  and  $O^{+q}$ ) precipitation, both from in situ observations of energetic ion losses in the middle magnetosphere near the Io plasma torus [Gehrels and Stone, 1983] and from inferences about the energy required to produce auroral X rays with the intensity observed by the Einstein X ray telescope [Metzger et al.,1983]. The efforts to establish the identity of the precipitating auroral particles have been complicated yet further by the lack of S and O recombination lines in the FUV  $H_2$  auroral emission spectrum, which suggests that the FUV aurora are largely electron-excited [Waite et al., 1988]. It therefore appears that many different kinds of charged particles may be contributing to the excitation of Jupiter's various auroral emissions.

This paper reports on theoretical calculations of the Lyman alpha line shape expected from proton precipitation impinging on the  $H_2$  atmosphere in the Jovian auroral zone and compares these predictions with high-resolution Lyman alpha line profiles of the Jovian aurora obtained by Clarke et al. [1989] using the International Ultraviolet Explorer. These comparisons are used to determine the role of protons in these auroral emissions. Meinel [1951] used ground-based high-resolution spectroscopy of Doppler-shifted Balmer ( $H\alpha$ ) emission to study the contribution of proton precipitation to the Earth's aurora (cf. Rees, 1989). Similar techniques were applied by Clarke et al. [1989] to study the Jovian aurora using high-resolution Lyman alpha spectra taken with the IUE telescope. No red-shifted Lyman alpha emission with wavelength shifts as expected from energetic protons was observed. However, blue-shifted emissions resulting from fast atomic hydrogen with ten's of eV of translational energy were observed to make up around 50% of the auroral Lyman alpha emission. The lack of significant red-shifted emission suggests that protons are not the primary precipitating particle responsible for the bulk of the observed ultraviolet aurora at Jupiter. On the other hand, the presence of significant blue-shifted emission suggests significant energization and outflow of protons and H atoms and/or significant thermospheric winds as a result of auroral energy dissipation. For further discussion of the blue-shifted emission we refer the reader to Clarke et al. [1989] and Clarke et al. [1991] and for present purposes we concentrate on using the lack of significant red-shifted Lyman alpha emissions to set limits on the energy flux of allowable proton precipitation into the Jovian auroral atmosphere.

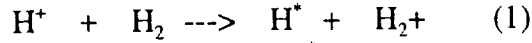
## The Model

The model employs a continuous slowing-down approximation for an equilibrated beam of energetic hydrogen atoms and protons incident on  $H_2$ . The energy loss is given by

$$-\left[\frac{dE}{dz}\right]_{H_2} = n_{H_2}(z) L_{H_2}(E) \sec(\theta),$$

where  $L_{H_2}(E)$  is the total energy loss function in  $H_2$  at energy  $E$ ,  $\theta$  is the mean pitch angle of the incoming particles with respect to the vertical, and  $n_{H_2}(z)$  is the number density of  $H_2$  at altitude  $z$ . The energy loss function for protons in  $H_2$  as a function of energy used in the model is that of Anderson and Ziegler [1977].

Two processes for the production of Lyman alpha photons by the interaction of the beam with the  $H_2$  atmosphere are considered:



Both protons and hydrogen atoms are present in the beam since electron stripping and charge exchange processes between the energetic beam and the  $H_2$  gas are constantly modifying the charge state of the beam (ie., the  $H^+/H$  ratio). Due to the energy dependence of these cross sections the beam changes charge state fraction as it dissipates energy in the  $H_2$  atmosphere. The energy-dependent proton-to-hydrogen atom fraction used in this calculation is taken from the work of Allison [1958]. Cross sections for production of Lyman alpha by process (1) at energies below 10 keV are taken from the work of Van Zyl et al. [1990] and above 10 keV from extrapolating using the energy dependence of the ionization cross section as measured by Birely and McNeal [1971].

Cross sections for process (2) are taken from Van Zyl et al. [1990]. Once again a reasonable extrapolation with energy above 10 keV is added on to model processes at higher energies. These cross section values for processes (1) and (2) are shown in Figures 1a and 1b, respectively. An estimate of the beams interaction with the dissociated (atomic) hydrogen component of the suggest that less than 5% of the emission can be attributed to such a source since at the altitude of maximum  $H^+/H$  beam energy deposition  $n_{H_2} \gg n_H$ .

The volume production rates as a function of altitude and energy were calculated by introducing an incident proton/hydrogen beam with a known flux within a specified energy bin. Each beam was then individually tracked as it deposited its energy within the atmosphere. The charge state of the beam (ie., proton to hydrogen ratio) was determined from the beam energy at each altitude step and the volume production rates for processes (1) and (2) were calculated at each altitude during the process of ion beam dissipation using the formulas

$$VP_{H^+}(z, E_{init}, E_z) = n_{H_2}(z) f_{H^+}^*(E_{init}, E_z) \sigma_{(1)}(E_z)$$

$$VP_H(z, E_{init}, E_z) = n_{H_2}(z) f_H(E_{init}, E_z) \sigma_{(2)}(E_z)$$

where:  $VP_i$  ( $i=H^+$  or  $H$ ) is the volume production at altitude  $z$ , initial beam energy  $E_{init}$ , and present beam energy at altitude  $z$  given by  $E_z$ ,  $f_{int}$  is the  $i=H^+$  or  $H$  flux from the initial beam of energy  $E_{init}$  now at the altitude - dependent energy  $E_z$ , and  $\sigma_i$  is the cross section

for Lyman alpha excitation by process i=(1) or (2) at energy  $E_z$ . The contribution to the Lyman alpha production as a function of energy and altitude is binned to allow computation of the Doppler-shifted Lyman alpha line profile. The production of Lyman alpha that results from secondary electron production is not included in the present calculation since these emissions are created virtually in the rest frame of the background gas and thus do not contain an observable red-shift.

A precipitating energetic proton spectrum is modeled by taking the Jovian magnetospheric proton spectrum from the Voyager LECP data of Krimigis et al. [1981], scaling it to the desired energy flux, and introducing it into the top of the atmosphere (see Figure 2). The model  $H_2$  atmosphere was taken from the earlier auroral electron modeling of Waite et al.[1983] and is shown for reference in Figure 3. Also shown in Figure 3 is the approximate altitude range for the Lyman alpha emission source and an approximate indication of the methane homopause below which  $CH_4$  absorption of Lyman alpha could affect the results. The beam flux has been normalized to produce an integrated energy flux of  $20 \text{ ergs cm}^{-2} \text{ s}^{-1}$ , which is approximately the flux that would be required to produce the observed  $H_2$  Lyman and Werner band systems, UV emissions [Horanyi et al.,1988]. A mean angle of  $30^\circ$  between the magnetic field direction and the IUE view direction was adopted for the observational viewing geometry. The broadening of the line emission from the "actual" pitch angle distributions of the ions (and charge exchanged neutrals) were not accounted for, but were not expected to add considerable broadening beyond the effects brought on by the assumed initial beam energy distribution and subsequent energy decay within the upper atmosphere which are properly accounted for by these calculations.

## Results and Conclusions

Red-shifted emission intensities that results from a proton distribution with a total energy flux of  $20 \text{ ergs cm}^{-2} \text{ s}^{-1}$  are shown in Figure 4 along with representative IUE Lyman alpha spectra from Clarke et al. [1991]. The location of the peak of the red-shifted Lyman alpha emission is determined by the convolution of the energy dependence of the Lyman alpha production cross sections at low proton/hydrogen energies and the tail at longer wavelengths (above  $1220\text{\AA}$ ) is directly related to the initial beam distribution. The location and shape of the red-shifted Lyman alpha peak from our calculations has been compared to similar observations of terrestrial Lyman alpha from the auroral zone [Ishimoto et al., 1989] and has been shown to be consistent with their results. Not shown in this figure is a 15-30kR Lyman alpha emission at line center ( $1215.7\text{\AA}$ ) which would result from secondary electrons produced by the beam atmosphere interaction impinging on atmospheric H and  $H_2$ . These secondary electron-generated emissions were not explicitly calculated since they result in no "red-shifted" emission. Such emissions would be easily observable by the IUE telescope. Clarke et al. [1989] did not, however, observe such emission intensities at these wavelengths. Clearly, therefore the observed aurora does not contain a proton energy flux large enough to produce the observed  $H_2$  Lyman and Werner bands. However, a smaller flux of protons is possible given the constraints of the IUE Lyman alpha line profiles. The upper limits of proton precipitation allowed by the observations can be calculated by retaining the same form of the proton energy distribution

as described above and by scaling down the energy flux to match the levels of red-shifted emission seen in the observations. Comparison of the observations with the model line profile suggest that protons comprise 5% or less of the particles responsible for the bulk of the Jovian ultraviolet aurora [cf., Broadfoot et al., 1981]. We note, however, that these results are weakly dependent on the energy spectrum of the precipitating protons. Given the present available data and the model, it is difficult to envision a scenario where protons would be responsible for over 10% of the observed auroral ultraviolet emission. More energetic proton beams ( $>> 1$  MeV) that deposit the bulk of their energy below the hydrocarbon absorption layer are not ruled out by the present observations, but they also cannot contribute to H<sub>2</sub> band ultraviolet auroral emissions.

The results reported here set useful constraints on magnetospheric processes responsible for auroral particle precipitation and add yet a further piece to the ongoing puzzle as to the identity of the particles responsible for Jovian auroral observations. Perhaps in situ confirmation of these results will be possible during the high-latitude encounter of Ulysses with Jupiter in January-February of 1992. In addition, high-resolution spectra at Lyman alpha by HST may provide additional observational constraints on auroral proton precipitation.

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## Figure Captions

Figure 1: Cross sections for Lyman alpha excitation of a) protons on H<sub>2</sub> and b) hydrogen atoms on H<sub>2</sub> taken from the work of Van Zyl et al.[1990].

Figure 2: Detailed spectral fit to the low-energy ion channels. Plotted (closed circles) are the intensities measured in sector f (~90° from convection direction) of the PL02-PL07 channels. In this direction, the detector response is thought to be due to protons only. The dotted curve shows the thermal distribution obtained using parameters listed in the figure. The dashed curve indicates a power law fit with a spectral index of 2.8. The closed square is from the LEPT detector channel which is sensitive only to protons. [Krimigis et al., 1981].

Figure 3: H<sub>2</sub> model atmosphere altitude profile from Waite et al.[1983]. Also indicated on the figure are the altitude of the doppler shifted Lyman alpha emission and the approximate altitude of the methane homopause below which altitude Lyman alpha absorption by methane could significantly affect our results.

Figure 4: The brightness numbers as a function of wavelength for both the model and the IUE SWP spectra (December, 1986). The brightness numbers assume that the emitting region is an auroral zone which is diffuse East-West (i.e. fills the 9 arc second large aperture) and is less than the IUE spatial resolution of 5 arc seconds North/South (i.e. is unresolved). Figure 4(a) shows the IUE SWP 29880 spectra data compared to a proton aurora energy flux of 20 ergs cm<sup>-2</sup>s<sup>-1</sup> which is roughly that required to account for the H<sub>2</sub> Lyman and Werner band emissions that were observed. Figure 4(b) shows a comparison of new IUE SWP spectra 44340 and 44342 with a 5% intensity of the 20 erg cm<sup>-2</sup>s<sup>-1</sup> aurora (1.0 ergs cm<sup>-2</sup>s<sup>-1</sup>) to illustrate the emission allowed by the present observations.

### **Acknowledgements**

Partial support for this work has been provided by NASA Planetary Atmospheres grant NAGW-1657, NASA IUE and ROSAT Observations of Jupiter's Auroral grant NAG5-1429, and by SwRI Internal Research project 15-9634.

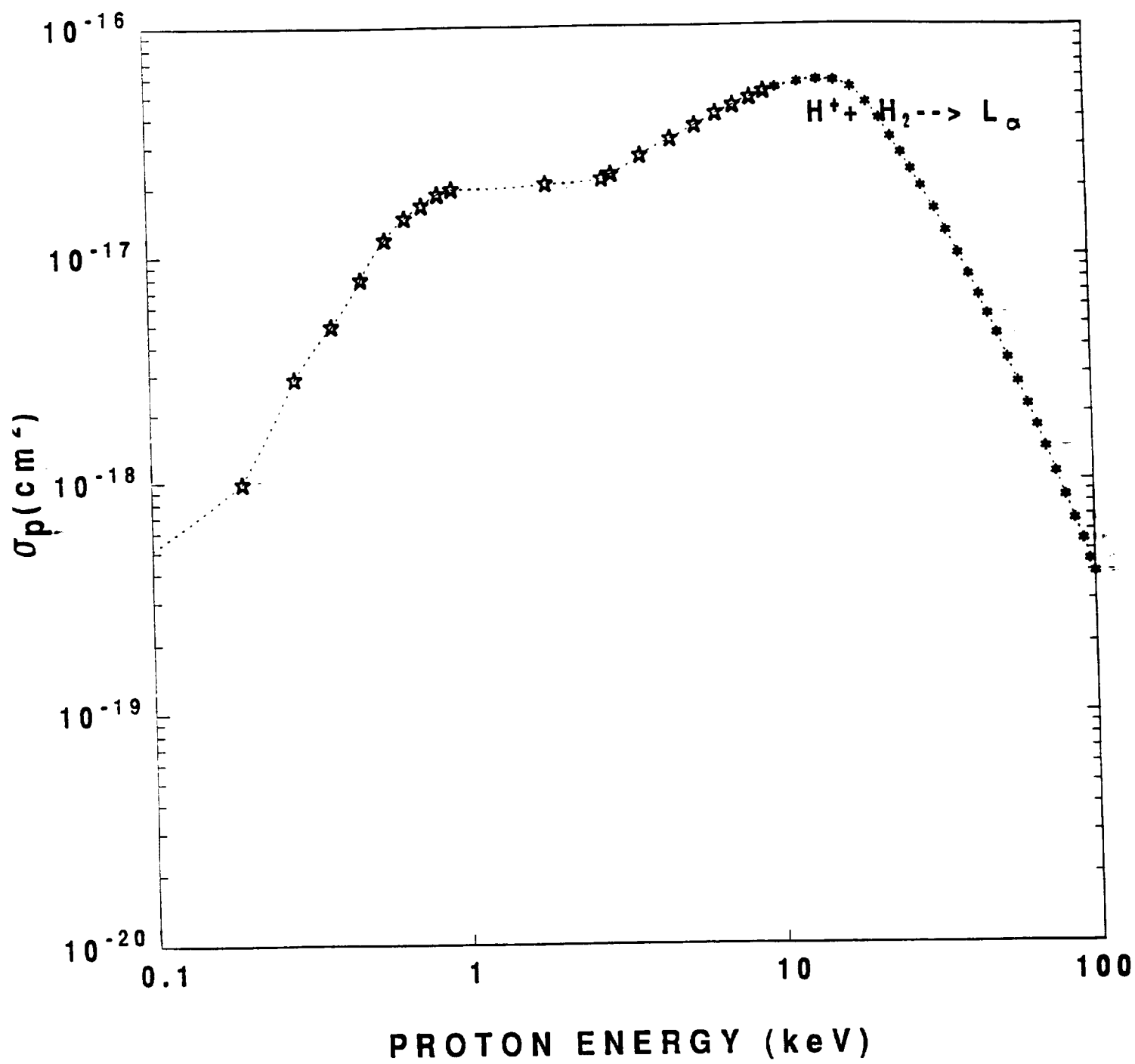


Figure 1a



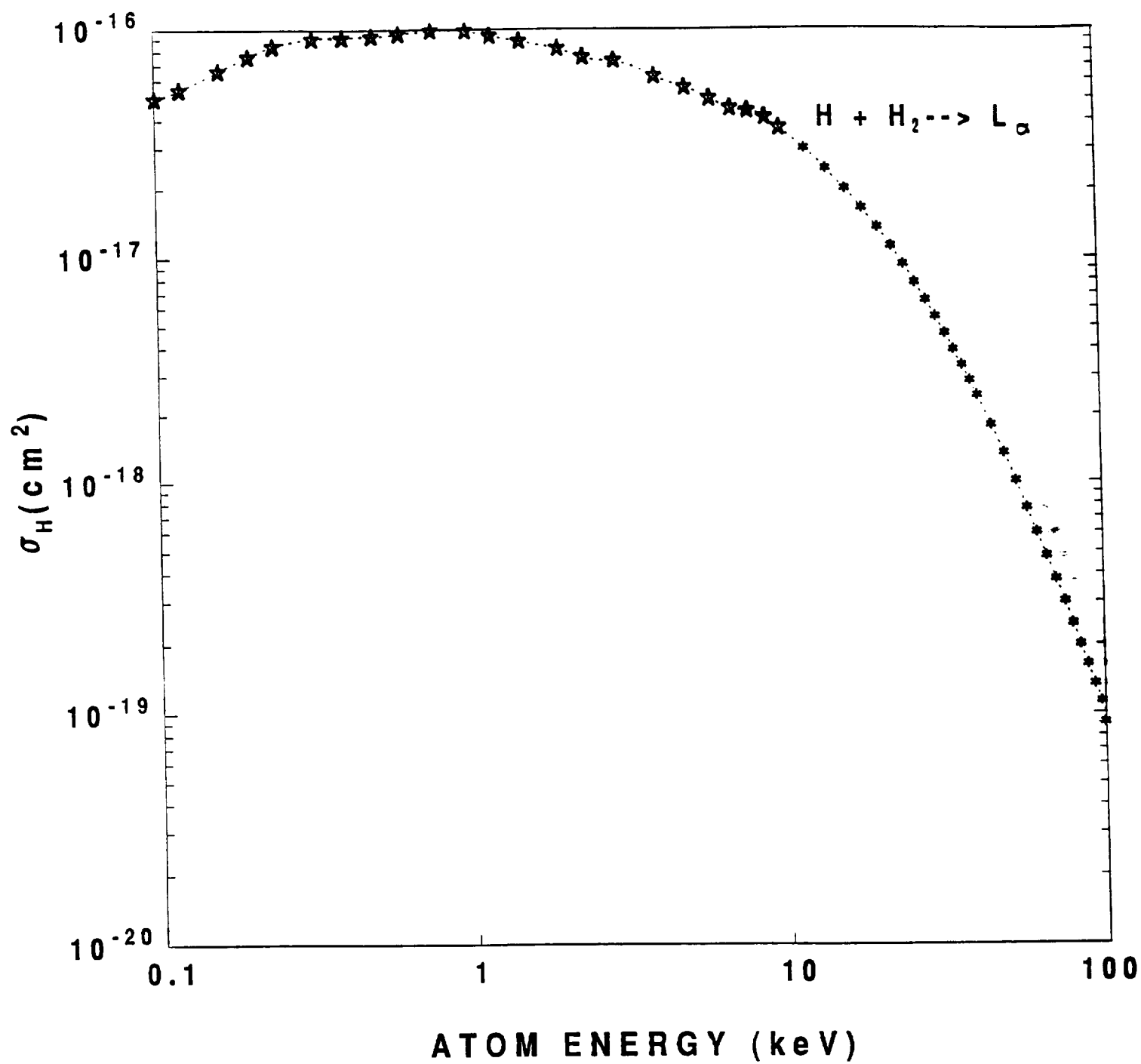


Figure 1b

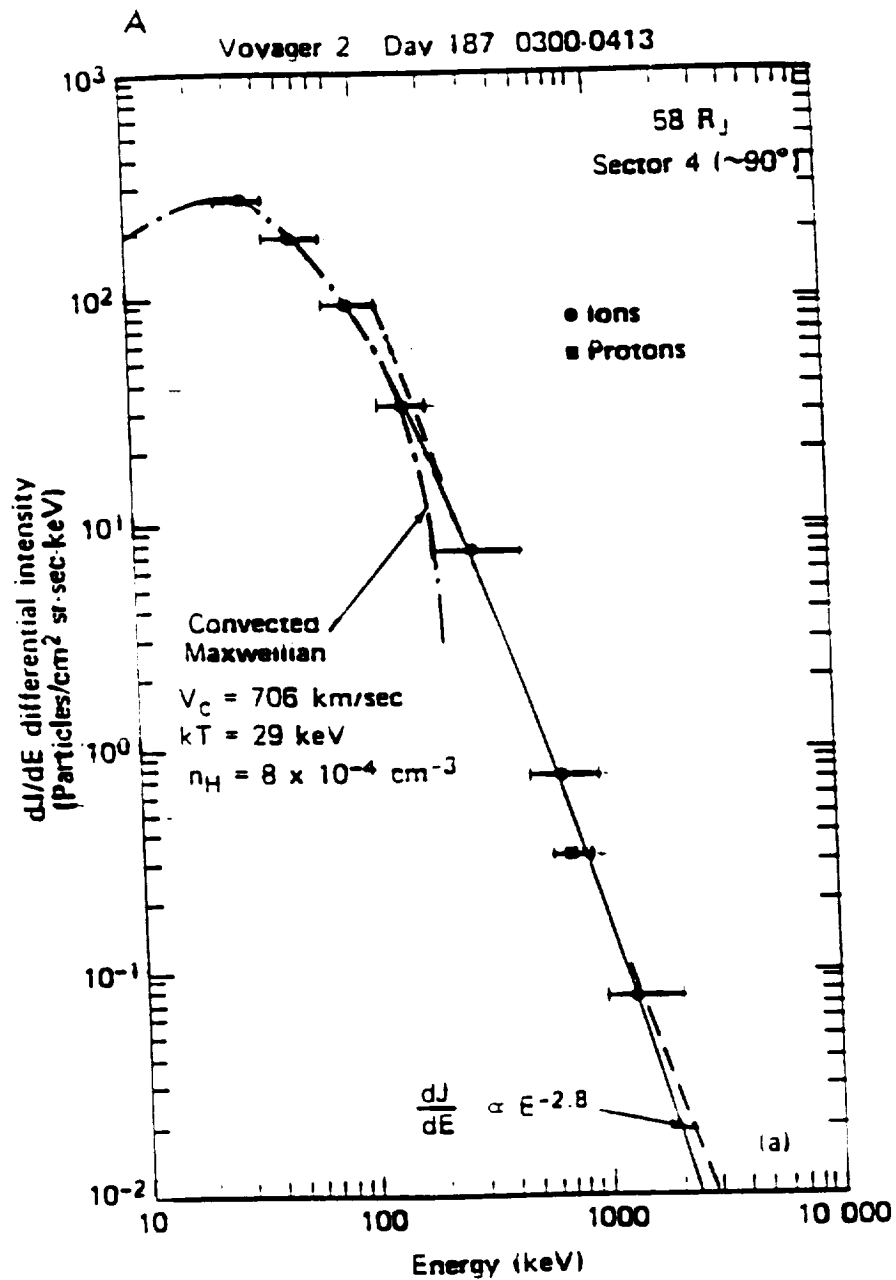


Figure 2

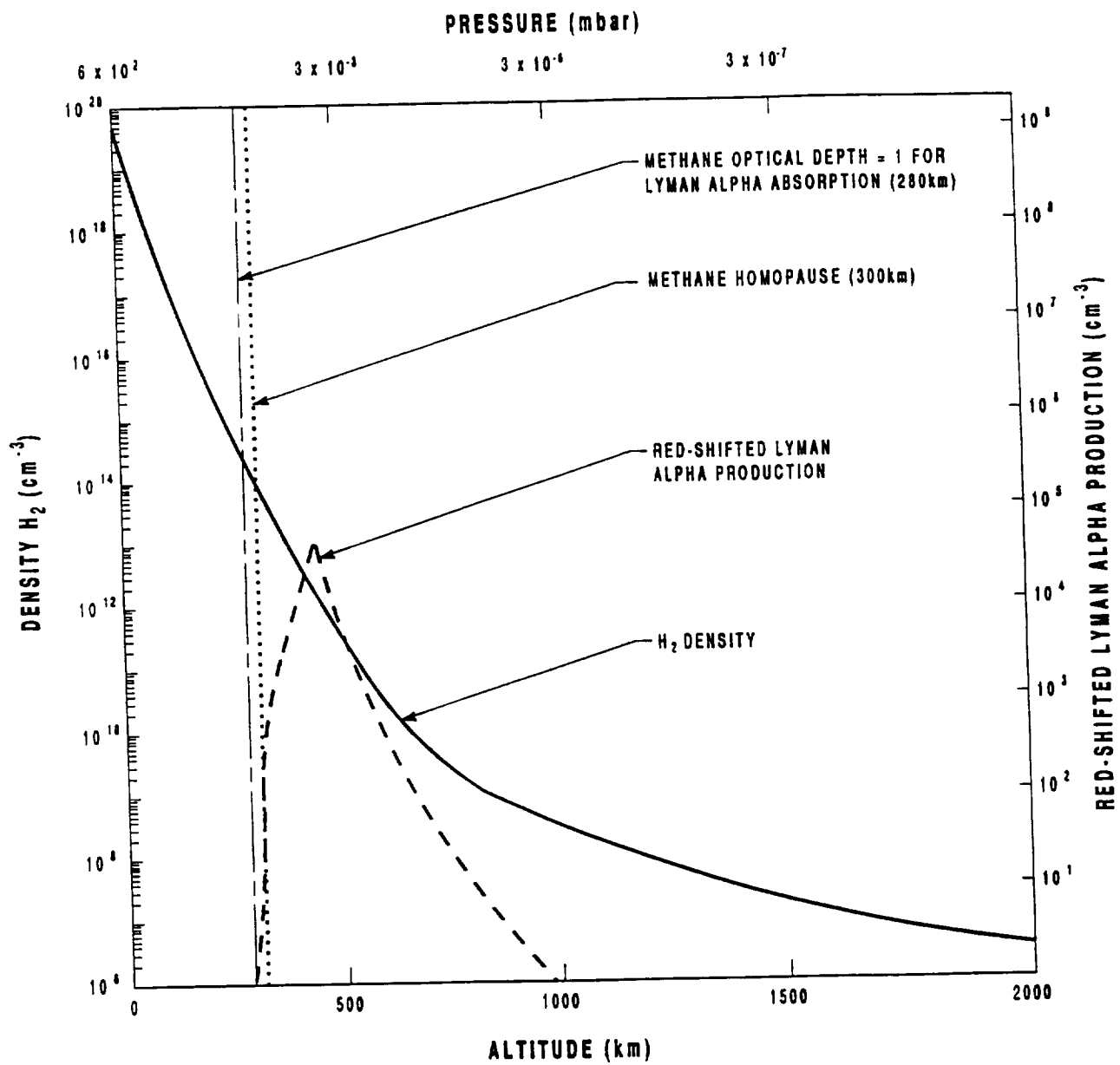


Figure 3

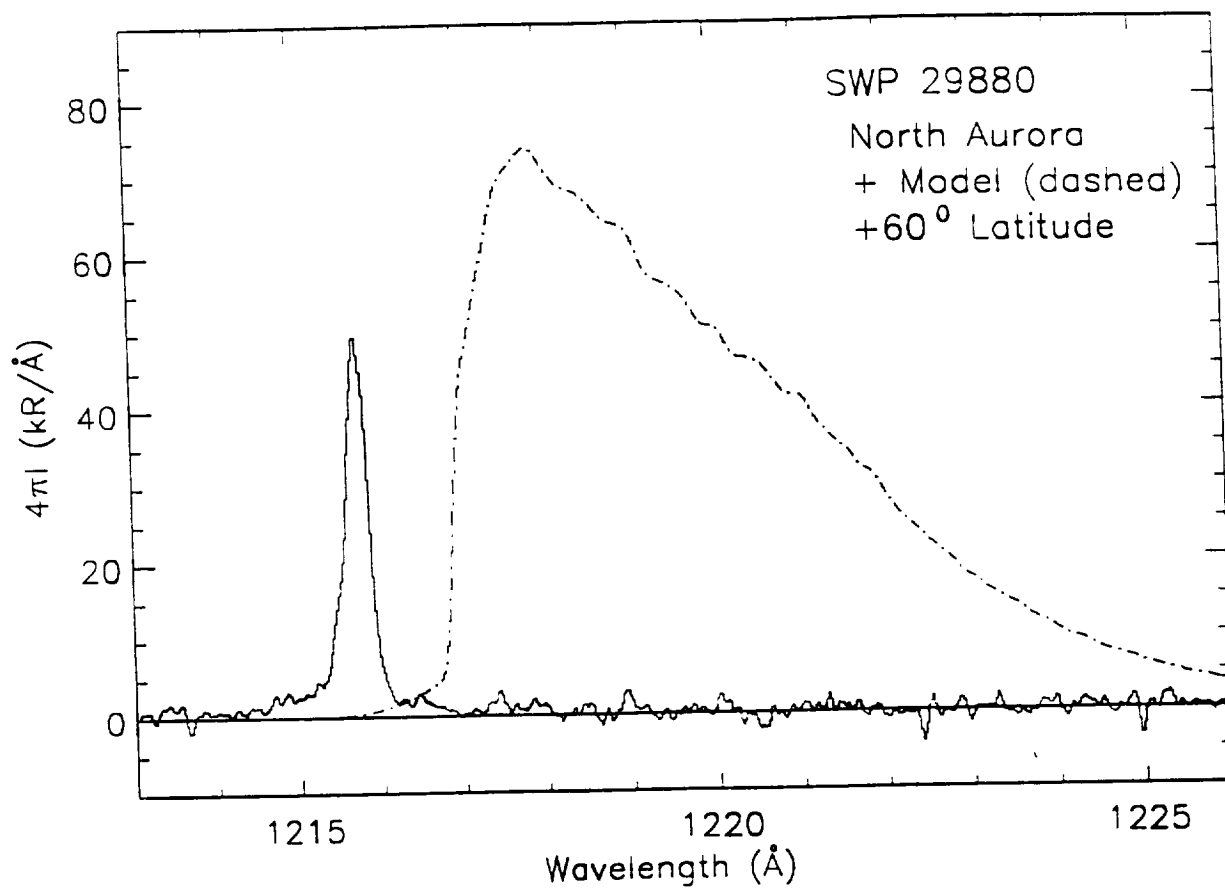


Figure 4(a)

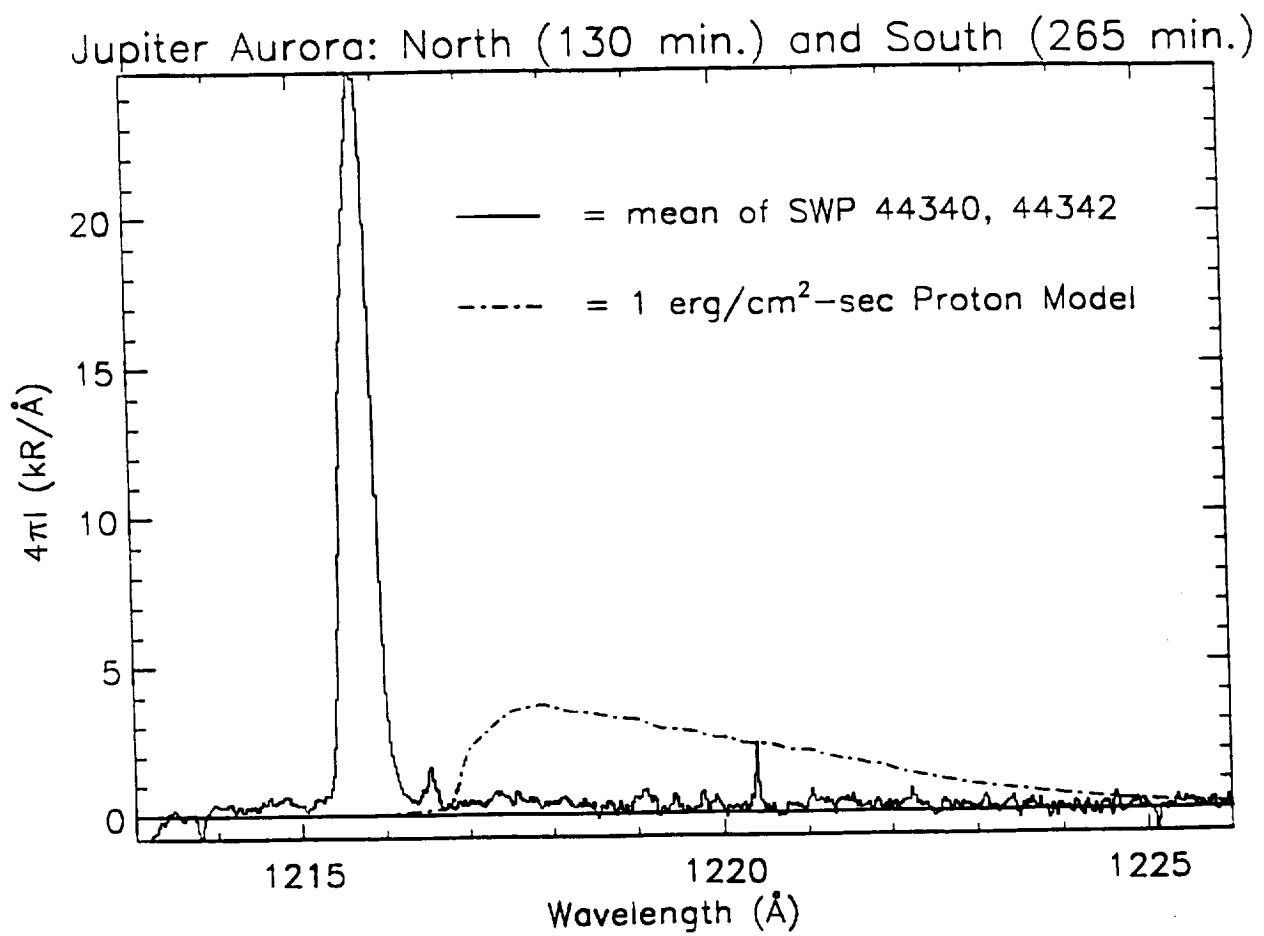


Figure 4(b)

## APPENDIX D